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The Four Florida Hurricanes of 2004 and Their Impact on the Fleet

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14. ABSTRACT

In 2004, four hurricanes (Charley, Frances, Ivan, and Jeanne) made landfall in the United States within 6 weeks. Each of these storms posed significant challenges to forecasters and Navy Fleet Commanders alike, particularly with respect to making sortie decisions and preparing Naval Stations for the approach of destructive weather. Sortie decisions are now based on the location of >50 kt wind and >12 ft seas, and unnecessary sorties are viewed as wasteful of resources. This Memorandum Report has two purposes: (1) to review the concerns and requirements of Naval Commanders with respect to safeguarding stations, ships, planes, and personnel from the destructive powers of tropical cyclones (TCs); and (2) to use this context as a framework to learn from the track and intensity forecasts of the four "Florida Hurricanes" of August through September 2004. In this Memorandum Report, a brief discussion of Navy Guidelines and hypothetical scenarios regarding avoidance of TCs at sea, as well as Sortie Conditions (SCs) and Tropical Cyclone Conditions of Readiness (CORs) is presented first. Review of the track and intensity forecasts in the cases of Hurricanes Charley, Frances, Ivan, and Jeanne follows. A Summary and Conclusions section presents lessons learned from the experience as well as suggestions on how guidance provided to the Navy for the purposes of setting CORs and ordering sorties could be improved.

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Abstract

In 2004, four hurricanes (Charley, Frances, Ivan and Jeanne) made landfall in the United States within 6 weeks. Each of these storms posed significant challenges to forecasters and Navy Fleet Commanders alike, particularly with respect to making sortie decisions and preparing Naval Stations for the approach of destructive weather. Sortie decisions are now based on the location of > 50 kt winds and > 12 ft seas, and unnecessary sorties are viewed as wasteful of resources. The purposes of this Memorandum Report are twofold: (i) to review the concerns and requirements of Naval Commanders with respect to safeguarding stations, ships, planes, and personnel from the destructive power of TCs; and (ii) to use this context as a framework to learn from the track and intensity forecasts of the four "Florida Hurricanes" of August through September, 2004. In this Memorandum Report, a brief discussion of Navy Guidelines and hypothetical scenarios regarding avoidance of TCs at sea, as well as Sortie Conditions (SCs) and Tropical Cyclone Conditions of Readiness (CORs) is presented first. Review of the track and intensity forecasts in the cases of Hurricanes Charley, Frances, Ivan, and Jeanne follows. A Summary and Conclusions section presents lessons learned from the experience as well as suggestions on how guidance provided to the Navy for the purposes of setting CORs and ordering sorties could be improved.

1. Introduction

From late August through September 2004, four hurricanes made landfall in Florida. During that five-week period, U. S. Navy Fleet and Installation Commanders had to make a variety of decisions regarding whether or not to sortie ships and aircraft from Naval Station Mayport and NAS Jacksonville, as well as what disaster preparedness measures to take to safeguard the bases, piers, airfields, buildings, and personnel that stood in the forecast path of these storms. These decisions are governed by the setting of Sortie Conditions and Tropical Cyclone Conditions of Readiness (SCs and CORs, respectively), where the former guidance assists individual ship and squadron commanders with sortie planning and execution, and the latter assists Naval Station and installation commanders with taking appropriate precautionary measures ashore to safeguard property and life. Furthermore, ships at sea also have specific guidance regarding the safe distance to be maintained away from tropical cyclones (TCs). Finally, the cost of sorties (particularly fuel) and disaster mitigation procedures outlined within the CORs are prohibitive if they prove to be unnecessary. That is, commanders no longer feel that they have the fiscal luxury of simply taking maximum precautions ashore and sending away hundreds of airplanes and ships because a TC is forecast to approach close to their bases. Accurate 120-h to landfall track and intensity forecasts, to include radius of storm- and gale-force winds, rate of dissipation of damaging winds, wave heights and the "sea bubble," storm surge, and flooding potential, are essential if Naval Commanders are to avoid ordering unnecessary sorties and excessive safeguards ashore, and yet avoid harm to ships, aircraft, facilities and personnel. The purposes of this paper are twofold: (i) to review SCs, CORs, and the concerns and requirements of Naval Commanders with respect to safeguarding stations, ships, planes, and personnel from the destructive power of TCs; and (ii) to use this context as a framework to learn from the track and

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intensity forecasts of the four "Florida Hurricanes" of August through September, 2004, while suggesting improvements in support provided to Naval Commanders. Thus, a brief discussion of Navy Guidelines and hypothetical scenarios regarding avoidance of TCs at sea, as well as SCs and CORs is presented first. Review of the track and intensity forecasts in the cases of Hurricanes Charley, Frances, Ivan, and Jeanne follows. A Summary and Conclusions section presents lessons learned from the experience as well as suggestions on how guidance provided to the Navy for the purposes of setting CORs and ordering sorties could be improved.

2. Navy Guidelines

One well-known Fleet Requirement (originated by the Commander, Pacific Fleet nearly ten years ago) requires that tropical cyclone track forecasts provided to the Fleet in the western North Pacific be accurate to within 50, 100, and 150 n mi at 24, 48, and 72 h, respectively. When at sea, ships are required to remain 300 n mi from the center of a TC, and in general avoid regions where > 35 knot winds and 12 ft seas are observed or forecast. When a TC approaches a Naval Station, the station commander initiates a specific set of rehearsed and pre-determined disaster preparedness actions that are triggered based on the time interval that 50 kt winds are anticipated "on-station." Measures appropriate to each individual station, based on its location, mission, and specific vulnerability to TC-generated winds, storm surge, waves and flooding are taken according to the following timetable of " Tropical Cyclone Conditions of Readiness (CORs):"

Tropical Cyclone COR 5	> 50 kt sustained winds possible within 96 h
Tropical Cyclone COR 4	> 50 kt sustained winds possible within 72 h
Tropical Cyclone COR 3	> 50 kt sustained winds possible within 48 h
Tropical Cyclone COR 2	> 50 kt sustained winds possible within 24 h
Tropical Cyclone COR 1	> 50 kt sustained winds possible within 12 h

An additional set of conditions dictates the timeline for execution of a sortie of aircraft and/or ships. These are operational in nature, in that they reflect the Fleet Commander's anticipation of an execution order to sortie. These are collectively referred to as Sortie Conditions (SCs) and are listed below:

SC "C" (Charlie)	Prepare to sortie within 48 h
SC "B" (Bravo)	Expected sortie within 24 h
SC "A" (Alpha)	Commence sortie to sea

Sortie of ships and aircraft should be completed before the onset of sustained >50 kt winds and 12 ft seas on station. It is almost always anticipated that the arrival of high seas due to TC-generated swell (the so-called "sea bubble") will arrive on station before damaging winds; thus, the expected onset of seas exceeding 12 ft is critical in the sortie decision timeline. Recall further that once at sea, Navy guidance requires that the ships remain 300 n mi away from the center of the TC, so a completed sortie should permit ships the opportunity to evade the TC accordingly. Many factors influence the smooth execution of a sortie, such as the harbor characteristics, winds and seas observed during the sortie, number of vessels ordered to sea, their size, their maximum speed, and number of available tugs and linehandlers. A smoothly executed sortie at a large Naval station (e.g., Norfolk) could take 12 h or more to complete. A sortie during deteriorating conditions becomes especially challenging when handling ships as large as

carriers, and the entire fleet sent to sea is only as "fast" and "safe" as the slowest (or last departing) ship. That is, completion of the sortie must permit the last ship to leave, and the slowest ship to depart, before 50+ kt winds and 12+ ft seas are observed, yet still steam at least 300 n mi ahead of the TC center. If the sortie commences after regular working hours, commercial tugs and civilian Public Works personnel who assist in the sortie will all incur overtime charges. Sorties of ships and aircraft can be extremely expensive, and while no one will argue that the cost of a sortie is far less than the cost of repairing or replacing severely damaged warships and aircraft, current fiscal pressures mean ordering a sortie only when absolutely necessary. The same logic also applies to setting CORs; excessive precautions, while erring on the side of safety, are also wasteful of scarce budget resources.

It should be pointed out that given the cost of fuel in particular, Fleet Commanders and the Commander, Fleet Forces Command (CFFC) who are painfully aware that unnecessary sorties and disaster preparedness incur significant costs, yet do not wish to subject ships, aircraft and personnel to unacceptable and preventable hazards. Operational risk management paradigms will guide the decision-making process during hurricane season, based on "acceptable risk." That is, if it is believed that a Naval Station will experience passage of a storm with ***sustained winds < 50 kt (i.e., gale-force, but not sustained storm-force winds)*** so that damage to aircraft, ships, and piers, if any: (i) does not compromise mission-oriented operational readiness; and (ii) costs much less than a sortie, with no loss of life and minimized risk of damage, then a sortie will not be ordered.

Three hypothetical scenarios (using actual NHC track forecasts to illustrate the hypothetical scenario) will be presented to illustrate the difficulty of making decisions regarding sorties and TC avoidance[1]. In the first of these, consider a TC forecast to translate poleward west of Cuba before recurving poleward over the Gulf of Mexico (Fig. 1). Consider that the forecast track may be expected to shift westward, as previous track forecasts (not shown) have been steadily adjusted to the west. A possible evasion route to the western Gulf (red, solid line) might have been advisable, as the hurricane is expected to pass closer to Florida than to the western edge of the Gulf. However, if the forecast track continued to shift westward, that evasion route becomes less desirable, as the hurricane could trap underway ships in the extreme western Gulf. An alternate route (dashed line) to the east has several potential disadvantages: (i) it is longer; (ii) it "crosses the T" by passing in front of an oncoming hurricane and exposing vessels to its most dangerous semicircle (to the east of the TC center); and (iii) requires an earlier sortie order in advance of landfall than the western route (i.e., likely based on 96- and 120-h track forecasts) so that ships can pass clear of the TC, avoid 35 kt winds at sea, and remain 300 n mi away from the TC center. In this scenario, the Fleet Commander would likely have waited until the 36-h and 48-h track forecasts before setting SC "B," passing up the opportunity to egress the Gulf through the Florida Straits as an evasion alternative, but retaining the option to modify the eastern evasion route by moving down the west coast of Florida.

[1] While real data from cases in 2004 is used to make the points in the following discussion, the intent is to highlight three main, basic scenarios that Fleet Commandeers face repeatedly: a TC that enters the Gulf of Mexico, a TC that unexpectedly veers toward a Naval Installation, and a TC that comes close but is apparently headed away from a Naval Installation.

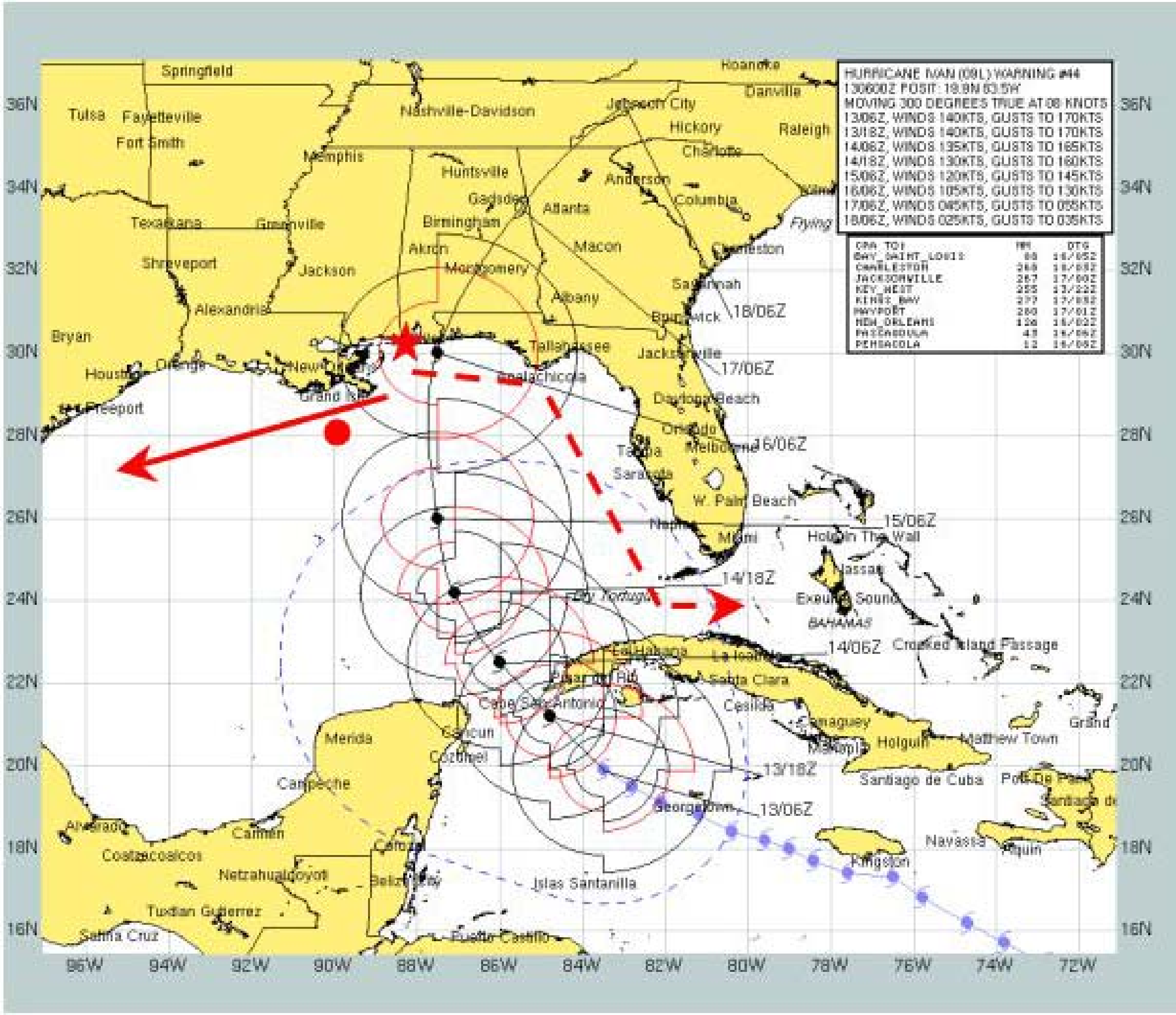

Fig. 1. 120-h NHC track forecast in the case of Hurricane Ivan (September 2004), used to depict a hypothetical scenario of a Gulf of Mexico TC. Thin, solid black (red) semicircles show location of tropical storm- (hurricane-) force winds. Heavy, solid (dashed) red lines show hypothetical egress paths for ships sortied from the Gulf Coast (red star), or already underway and operating in the Gulf of Mexico (red dot).

Next, a hypothetical scenario with a recurving storm off the east coast of Florida is depicted (Fig. 2). The 120-h forecast (Fig. 2) forecasted recurvature off of the U. S. Coast, away from Jacksonville. Now assume that the storm translated as forecast until the position indicated at the 72-h forecast (Fig. 2), but then the steering flow of a strengthening subtropical ridge cell instead drove the storm westward along the solid, red path directly toward Jacksonville. If this new track (solid, red line) did not become known until the 48-h forecast, the Fleet Commander would suddenly have to consider a previously unneeded sortie, before the swell pushed ahead of TC's arrival results in seas > 12 ft. Thus, if the 48-h forecast resulted in high confidence in landfall near Mayport, SC "B" and COR "3" would be set. A sortie would be ordered (SC "A") if >50 kt winds were forecast at 36-h, and would commence before onset of > 12 ft seas, although the safest egress route "crosses the T" of a TC that is translating farther westward than forecasted,

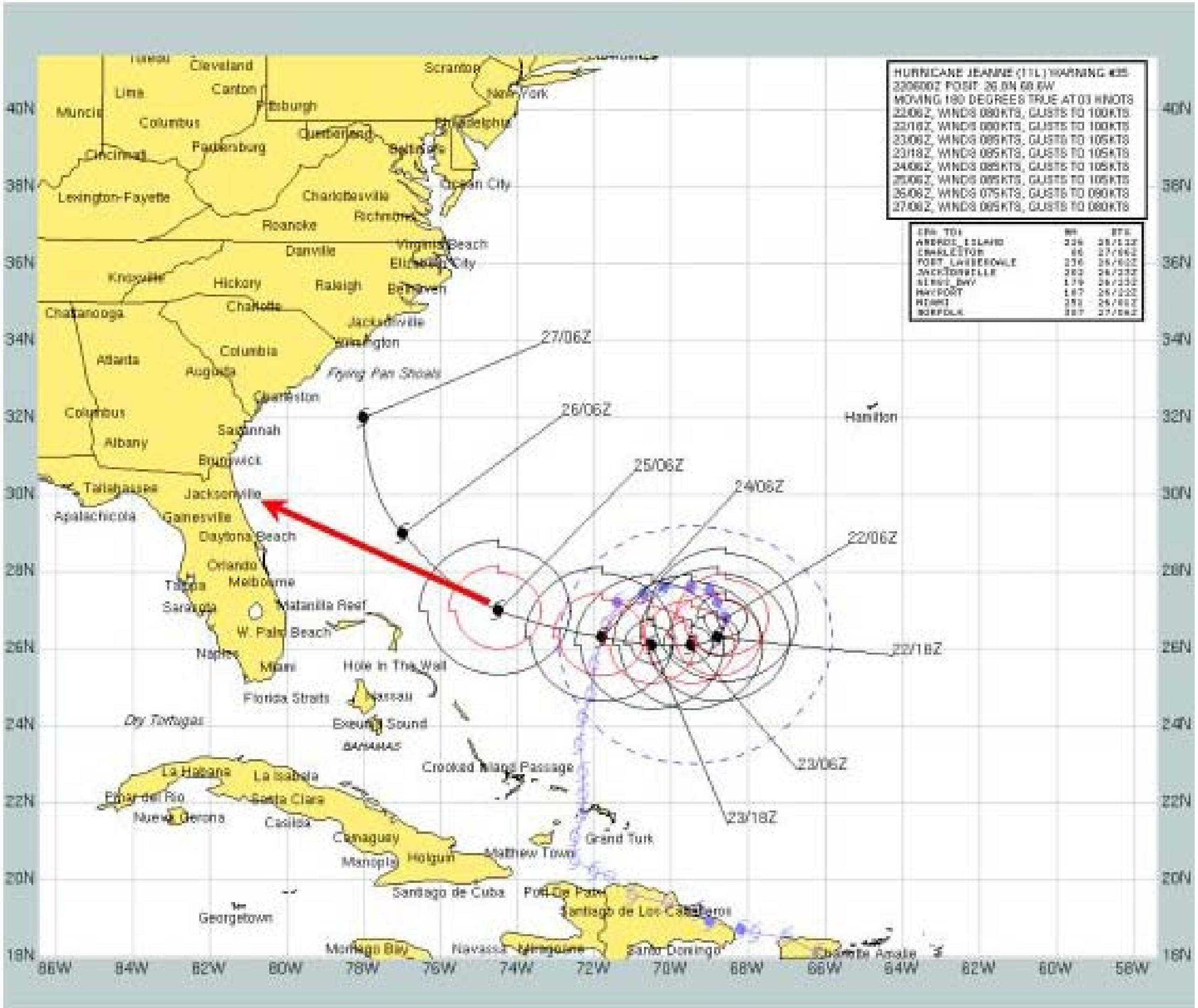

Fig. 2. Scenario with a recurving TC off the east coast of Florida. The red arrow depicts a hypothetical path departing from the forecast guidance at the 72-h point.

and in so doing, could expose vessels to the dangerous semicircle if they do not egress quickly enough.

Consider a third hypothetical scenario in which landfall is forecast in the southern part of Florida's east coast, after previous track guidance over the last 36-h had shifted the official forecast sequentially westward, with landfall farther and farther to the south of Naval Station Mayport. At the time depicted in Fig. 3, the Fleet Commander will have remembered this westward change in the official National Hurricane Center (NHC) guidance. So long as the 48-h forecast takes the TC even farther to the west, then confidence in that forecast would preclude the need for a sortie, as landfall and recurvature would not have threatened Jacksonville with > 50 kt winds. If subsequent forecasts instead adjusted the track of the TC eastward toward Jacksonville, SC "B" might have been set with the caveat that a sortie order could follow

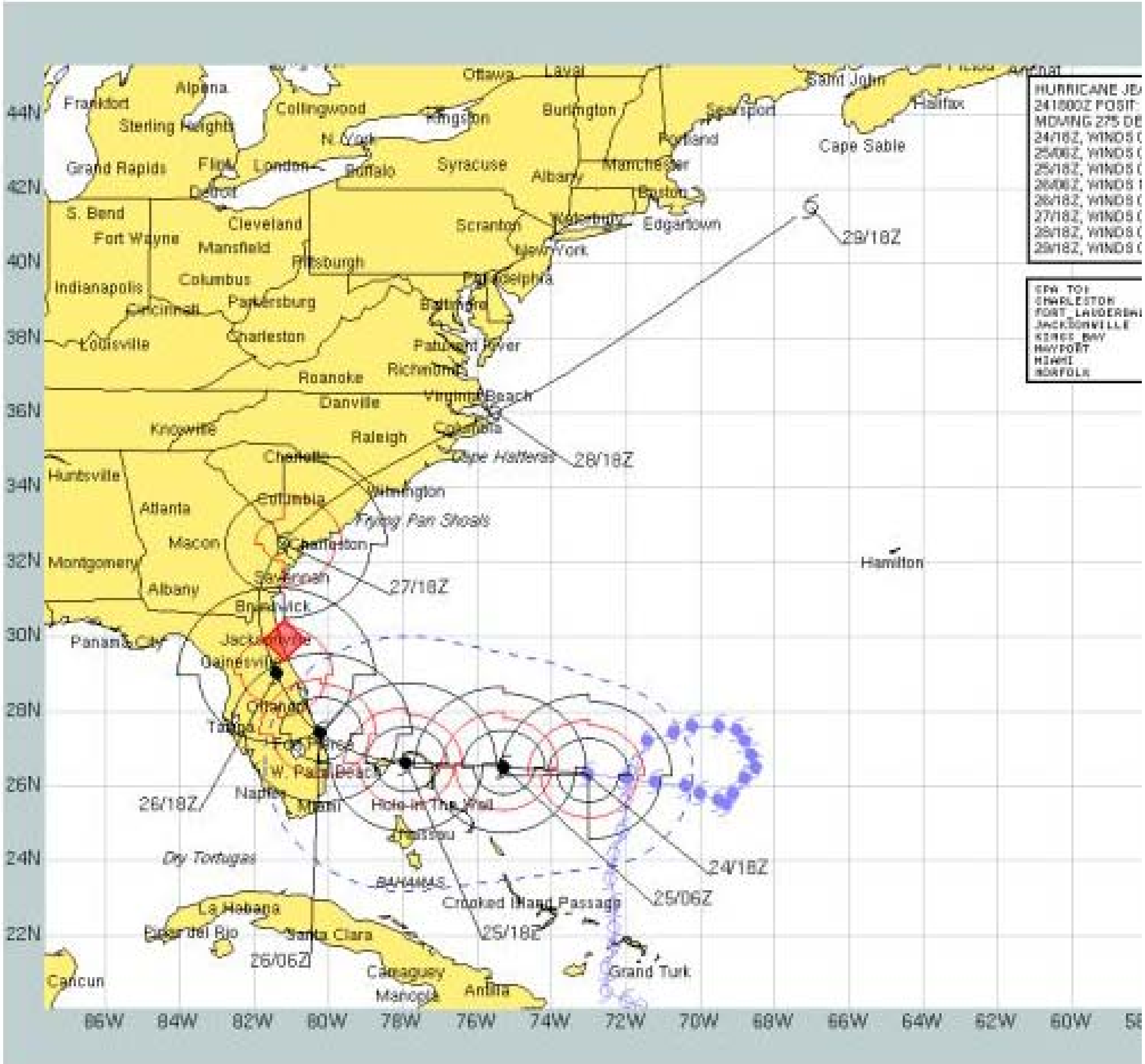

Fig. 3. NHC track forecast for Hurricane Jeanne at 1800 UTC 24 September, with the approximate location of Jacksonville-area Naval Stations depicted by a red diamond.

quickly. Smaller ships such as Minehunters (MHCs) and patrol craft might be moved to safe havens on inland waterways, although this would still leave them vulnerable to extreme storm surge. In the event of landfall south of Mayport, a final concern would be the rate of decrease of intensity while passing over land before approaching Mayport along a poleward path. An accurate forecast of the TC wind speed decay over land is required to permit the proper precautions to be taken. Presuming dissipation resulted in less than sustained 50 kt winds on station, the decision to weather the storm in port and not to sortie would likely be best, with no higher than SC B/COR 3 set at Naval Station Mayport and NAS Jacksonville as a precaution.

In the cases of Hurricanes Charley, Frances, Ivan, and Jeanne, the NHC analyses of the radii of 35 kt winds and 12 ft seas from the center of the TC every 6 h were combined into one data

set (Table 1). The number of analyses, means and standard deviations were grouped by TC quadrant and by storm intensity based on the Saffir-Simpson scale. The NHC analyses were based on a mixture of observations (e.g., dropwindsonde, aircraft measurement, radar wind data, etc) and empirical wind profiles based on a blend of physics (i.e., conservation of angular momentum less friction) and the observations. Notice that in the case of wave heights, the maximum and minimum radial distances of 12 ft + seas exceeded those for the 35 kt winds, and did not necessarily increase with the Saffir-Simpson intensity (Table 1, distances for the SE and SW quadrants not shown). In terms of criteria for TC avoidance while underway at sea, remaining 300 n mi away from the TC center may not keep vessels out of the 12+ ft seas region, which will require additional safe distance from the TC. In cases where the area of 12+ ft seas is particularly large, sorties would have to be completed even earlier. Thus, accurate forecasts of the 12 ft seas/swell contour through the life of the TC up to landfall would be extremely valuable in helping to determine the "last-possible" moment a sortie can be ordered so that the last ship departing avoids 12+ ft seas. Forecasts of anticipated storm surge also become especially important if weathering the storm in port, whether pierside, or in the case of smaller vessels, at an inland safe haven. That is, pierside fenders may be lifted by the surge above the pier level so that moored ships no longer are protected from direct contact with the wood, metal, and concrete pier structure. Potential for pier and ship damage exists in such an instance, even if sustained winds are not storm strength (> 50 kt).

A final point to be made is that Navy ships, with their sail area and tall masts, and Navy stations, shipyards and airfields, with their cranes, antennae, and control towers, will be subjected to stronger winds than those forecast or observed at the surface. Franklin et al. (2000) found that mean eyewall wind speeds at heights of 100 to 200 ft above the water were 108% and 115% of those observed at the surface, respectively. Using this thumbrule, 100 kt winds at the surface become Category Four strength (> 114 kt) 200 ft above water. Consider the large "sail area" of an aircraft carrier or amphibious assault carrier, where the flight deck might be 50 feet or more above the water, and the tops of the masts exceed 200 feet above the water. It is clear that winds stronger than those forecast for the surface will be pushing against the side of the ship or blowing through the masts and radar antennae. Sustained hurricane-force winds acting against such a sail area can literally rip a ship, even a large one, from its moorings and lines, and set it into other structures, ships, or aground. The damage and potential for loss of life in such a circumstance has been demonstrated time and again (e.g., in the Pacific where typhoons

	Max	Min	NW Mean	NW Std	NE Mean	NE Std	# Analyses
Cat 1	180 (600)	0 (50)	97 (225)	21 (143)	99 (226)	23 (161)	21
Cat 2	180 (600)	40 (60)	120 (341)	25 (183)	123 (327)	32 (167)	19
Cat 3	180 (480)	80 (100)	120 (225)	23 (94)	131 (247)	31 (124)	21
Cat 4	275 (480)	75 (60)	141 (245)	30 (63)	155 (299)	40 (57)	39
Cat 5	200 (360)	75 (140)	148 (252)	21 (51)	165 (298)	18 (58)	10

Table 1. Distances from the TC center (n mi) of 35+ kt winds and 12+ ft seas (listed parenthetically, in n mi), in the cases of Hurricanes Charley, Frances, Ivan and Jeanne. Max (Min) = maximum (minimum) distance observed in all cases for that category, which re segregated by Saffir-Simpson scale intensity at the valid time of that analysis. NW, NE refer to values in the Northwestern, Northeastern TC Quadrants respectively, with Std = Standard Deviation.

routinely strike the Naval Station at Guam as in the case of Supertyphoon Omar, 1992), and it should not be forgotten that ***sustained hurricane force winds are the primary and deadliest threat posed to ships, structures, and personnel, and are the primary reason to consider a sortie***.

3. Forecasts, Guidance, and Decisions Made During the Four Florida Hurricanes of 2004

The four hurricanes that struck Florida in 2004 presented numerous challenges to Navy Fleet Commanders. Each storm potentially required preparations at a number of Naval Stations simultaneously (e.g., Ivan for Naval Station Mayport, Naval Air Station Jacksonville, Naval Station Pensacola, and shipyards at Pascagoula, MS and Mobile, AL). After the danger passed from one storm, another storm followed in its wake three times within 6 weeks, which required urgent resumption of precautions and preparations in the face of "TC fatigue."

a. ***Hurricane Charley***. The path of Charley resulted in an oblique strike (Fig. 4) against the largely poleward-oriented west coast of Florida. Thus, the smallest deviation in Charley's northward track orientation would have produced significant differences in the location of landfall. Even small forecast errors would have resulted in very large point of landfall errors. Since much of the U.S. coastline is similarly oriented (with the exception of a west-to-east section of the Gulf Coast from the Texas-Louisiana border through the Florida panhandle), it is clear that the accuracy of landfall forecasts are complicated as much by coastal geometry as by the science of track forecasts.

The USS Yorktown (CG 48) was sortied from Pascagoula two weeks early due to concerns regarding Charley's forecast track into the Gulf of Mexico (Commander Second Fleet, 2005)[2]. Since the Yorktown was to leave anyway, the only costs associated with her "sortie" were minor and associated with the accelerated departure from a shipyard. The decision to send her early resembled the first scenario presented in the previous section. Later, the official forecast from 0500 EDT 12 August 2004 (not shown) put Charley essentially overhead of Mayport 48 h later with sustained 60 kt winds. Confidence in this forecast, together with Charley's subsequent rapid intensification, led to a decision by Fleet Commanders to sortie ships from Naval Station Mayport.

Another point in the case of Charley concerns intensity forecasts. The National Hurricane Center included intensity forecasts out to 120 h as part of their TC guidance product suite (in particular, the storm discussions available every 6 h). Satellite imagery, imagery analysis techniques (e.g., Dvorak), dropsondes, radar analyses (e.g., ground-based and airborne radars), direct airborne sampling, and other observations can be used to create a "best-guess" wind profile, quadrant by quadrant, for both the TC inner and outer circulations. Then, several statistical and numerical models are used, together with objective assessment of environmental conditions (e.g., vertical wind shear, sea-surface temperature, quality of outflow, atmospheric soundings and stability profiles) to generate TC intensity forecasts. DeMaria (1997) described each of the aforementioned intensity models in an informal reference available on the NHC Web Homepage at http://www.nhc.noaa.gov/aboutmodels.shtml.

[2] From phone conversation with Commander, Second Fleet METOC Staff.

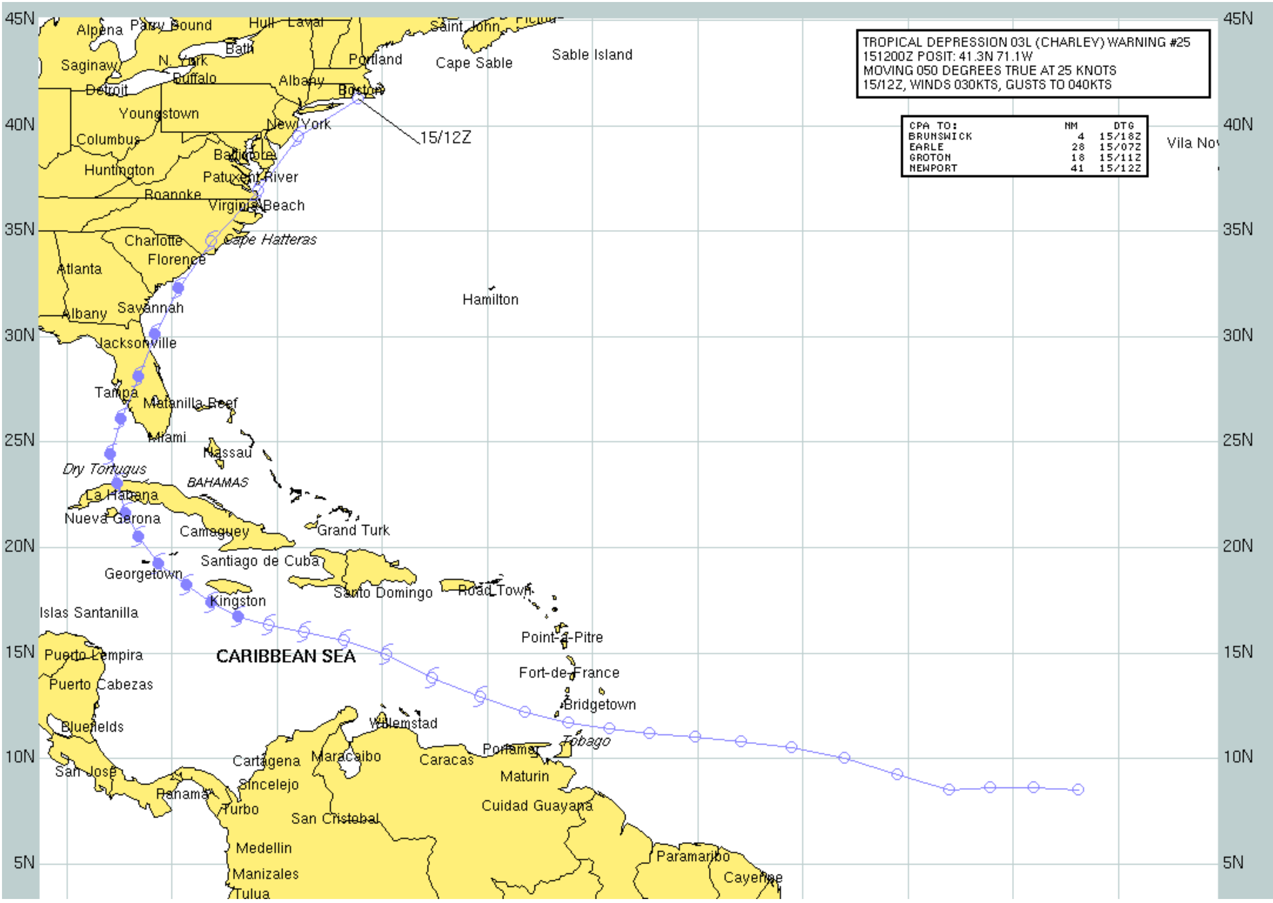

Fig. 4. The path of Hurricane Charley (light blue), with positions denoted every 6 h. Open circles denote location of Charley as a depression. (chart produced by ACTF, archived by Naval Research Laboratory (NRL), Marine Meteorology Division, 2004).

Starting with the intensity forecasts in the 1700 EDT 9 August 2004 discussion, the 12-, 24-, 36-, and 48-h intensity forecasts were compared to the verifying intensity to determine error (Table 2). (Table 2 does not contain this information.) In the above, a negative value indicated cases in which the forecasted intensity was less than observed. The mean error at these intervals was -4, -11, -18, and –22 kt, respectively, with standard deviations of 7, 2, 5, and 6 kt. The largest intensity forecast errors were observed from 1700 EDT 11 August to 1700 EDT 12 August 2004, during which time Charley became a hurricane with an increase in intensity of 25 kt, and during a period of rapid intensification on 13 August just before landfall on Florida. Using 1700 EDT 13 August 2004 as the landfall verification time, the intensity errors were –20 kt, -20 kt, -30 kt, and –35 kt (for maximum observed winds of 125 kt) at 12-, 24-, 36-, and 48-h forecasts.

Although intensity forecasts during such rapid intensification periods are regarded as having little skill, it would be a mistake to pay little attention to them. Review of official intensity forecasts for all four TCs (Charley, Frances, Ivan, and Jeanne) showed that > 90% of the errors were on the order of 5 to 10 kt for the 12- to 48-h forecasts. As shown above, larger errors occur during rapid intensification, especially when that rapid intensification was from tropical storm to hurricane. Since the COR depend on intensity it is important to predict intensity changes (i)

Time	Discussion Notes	Intensity Forecast (landfall)
1700 EDT 10 Aug 04	"…upper-level outflow looks strong and the shear is expected to remain weak over the next few days. Therefore conditions appear to be favorable for intensification."	75 kt
0500 EDT 11 Aug 04	"…outflow remains excellent…and there is no reason why steady intensification should not occur…"	75 kt
1100 EDT 11 Aug 04	"…There is well established upper-level outflow pattern and vertical shear is expected to remain low for the next couple of days…"	80 kt
1700 EDT 11 Aug 04	"…so the atmosphere is expected to remain favorable…and the ocean very favorable…for strengthening…"	90 kt
0500 EDT 12 Aug 04	"…the official forecast takes Charley to just shy of major hurricane status…but it could just as easily reach that threshold prior to landfall…"	95 kt
1100 EDT 12 Aug 04	"…there is a distinct possibility that Charley could be near major hurricane strength when it makes landfall along the Florida west coast…especially if it makes landfall along the Tampa Bay area and southward where the vertical shear will be less…"	95 kt
1700 EDT 12 Aug 04	"…upper-level outflow continues to improve and expand in all quadrants as the vertical shear has decreased significantly…given the impressive outflow regime that is forecast to develop over the Florida Peninsula and Eastern Gulf…major hurricane strength seems quite probable over the Southeastern Gulf of Mexico on Friday."	105 kt
0500 EDT 13 Aug 04	"…eye still remains well defined with about an 18 n mi diameter…Key West Doppler winds higher than 100 kt…The shear is forecast to be weak for the next 12 h and the water is warm. Therefore…..Charley is likely to strengthen before landfall…"	105 kt
1100 EDT 13 Aug 04	"…A closed 10-mile diameter eyewall persists and the pressure has dropped 5 mb…suggesting that there could be some additional strengthening during the next several hours before landfall…"	95 kt at 1100 EDT; 125 kt at 1400 EDT

Table 2. Text excerpts from NHC Discussions of Hurricane Charley. Times listed are all EDT with the landfall intensity forecasts verifying at 1700 EDT 13 August 2004.

when the storm deepens into a hurricane; and (ii) in the event of rapid intensification prior to landfall. The rapid intensification that preceded Charley's was mentioned in the NHC written discussions well before it occurred, even though official intensity forecasts did not reflect the quality insight in the foreboding text discussion, as the official intensity forecasts rely on statistical tools. Excerpts from the NHC discussions of Hurricane Charley are included in Table 2. Notice that almost 72 h from landfall on 13 August, the tone of these discussions set the stage well for anticipated strengthening. From then until landfall, the NHC discussions repeatedly noted that the environment provided excellent upper-level outflow, low vertical shear, and ample oceanic heating for Charley's subsequent intensification. Almost 36 h before landfall, the discussion text included the possibility of Charley becoming a major hurricane even though the official intensity forecasts never exceeded 95 kt until the 1700 EDT 12 August 2004 discussion less than 24 h before landfall. On 13 August, Charley translated over an ocean surface (along the southwestern coast of Florida) where sea-surface temperatures were quite favorable for Charley's intensification, exceeding 30 degrees C (Fig. 5). In the 0500 EDT 13 August 2004 discussion (the day of landfall, less than 12 h away), it was mentioned that Key West WSR-88D winds were higher than 100 kt, while conditions remained favorable for strengthening. NEXRAD Doppler reflectivity mosaics (Fig. 6) from approximately 0800 EDT until landfall indicated eyewall contraction and the development of an inner ring of strong reflectivity (implying intense rainfall in a region of vigorous convection, notice in particular Fig. 6e) as the storm translated over the warm water depicted in Fig. 5. Such developments in the radar imagery strongly suggested that significant intensification is taking place where the seas-surface temperature was favorable (Fig. 5), and in a location where an NHC Discussion (Table 2, 1100 EDT 12 August, more than 24 h prior to landfall) anticipated increased likelihood of Charley achieving major hurricane status. Finally, citing an 95 kt surface wind from an eyewall dropsonde that was four hours old in the 1100 EDT 13 August discussion, could have contributed to a false notion that only modest intensification as a Category 2 storm was likely, even though in that same discussion it was noted that the eyewall had contracted nearly 50% from 18 to 10 n mi in diameter. It is likely that the actual intensity of Charley at 1100 EDT was greater than 95 kt, since the 1400 EDT special discussion released by NHC described observations of 125 kt (Category 4). After 1100 EDT the rapid intensification was diagnosed by the NHC a scant few hours before landfall, which prompted release of that special discussion. The point is that careful review of the anecdotal evidence in the NHC discussions provided several clues that could have alerted experienced forecasters to be on the lookout for significant intensification of Charley as early as 48 hrs before landfall, with sufficient opportunity to later diagnose such intensification in the 8 hours that preceded landfall.

Now consider the impact of an "unexpected" landfall of a Category 4 storm in lieu of the anticipated Category 2 intensity. As described above, the Navy preparedness actions (CORs/SCs) for Charley were that it was already expected to arrive in the vicinity of Naval Station Mayport with 60 kt sustained winds, well before rapid intensification was diagnosed, and this had already prompted planning by Fleet Commanders for a sortie. Still, expectation well in advance of a powerful hurricane certainly commands more respect, greater caution, and fear of more devastation in the minds of emergency response planners, as well as Fleet Commanders. The rapid intensification of Charley, though not anticipated, was barely diagnosed in time for the execution of a sortie from Mayport, although that sortie did not begin until shortly before Charley's landfall. Of course, accurate landfall intensity forecasts and subsequent wind

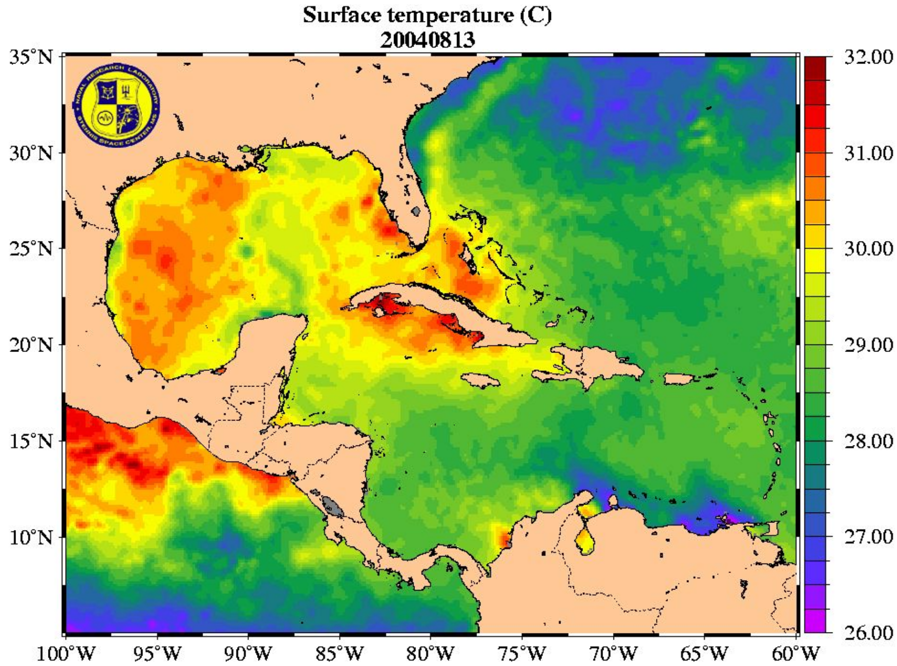

Fig. 5. SST plot from August 13, 2004 (Navy Research Laboratory (NRL), Stennis, Oceanography Division).

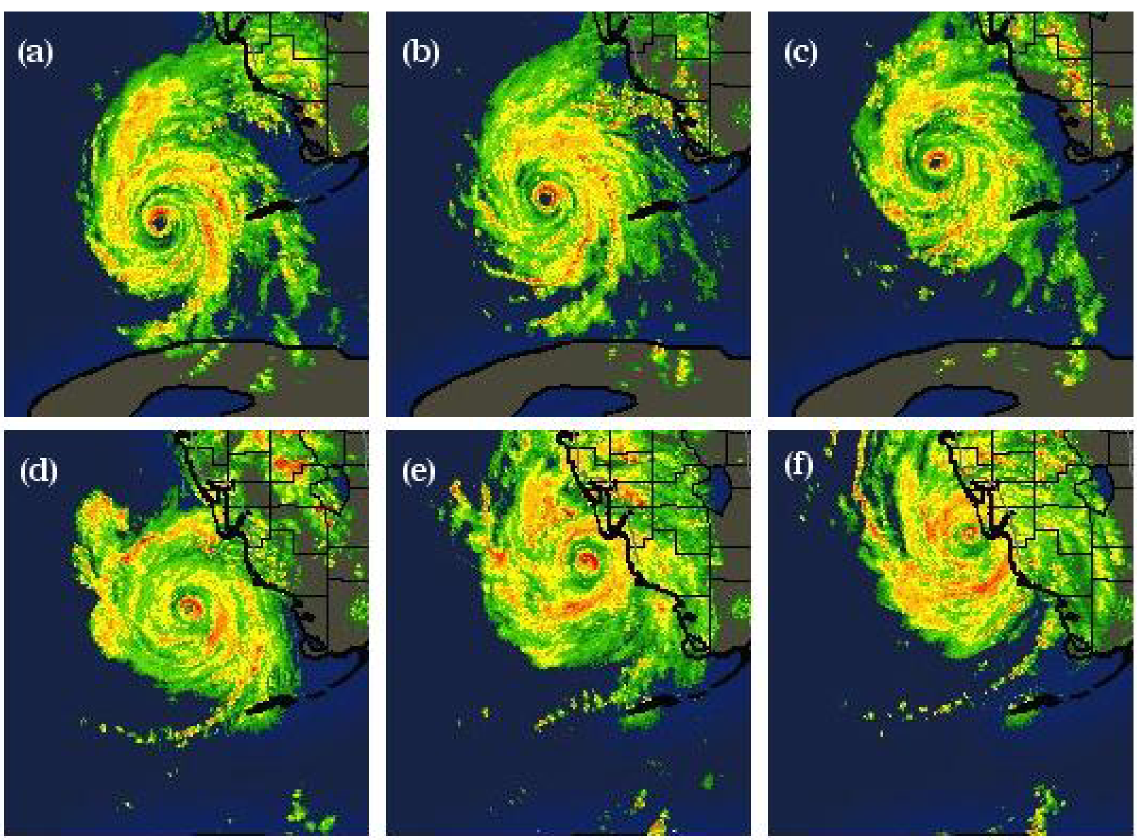

Fig. 6. NWS NEXRAD Reflectivity Composite Mosaics, 13 August 2004 at approximately (a) 0800, (b) 0930, (c) 1100, (d) 1300, (e) 1430, and (f) 1500 EDT. Notice contraction of eyewall and the development of an intense ring of convection around the eye throughout the period depicted.

dissipation forecasts[3] before the storm arrives over Mayport would have been useful in determining ahead of time whether or not a sortie would be necessary. A stern verbal discussion of the possibility of rapid intensification well in advance would have been quite useful, so that if continuing favorable conditions are subsequently diagnosed, emergency preparations can be urgently completed. In a sense, this would have been analogous to a "tornado watch" in that NHC could have cautioned Fleet Commanders that there was a good possibility for rapid intensification, and if subsequent diagnosis confirmed it, Fleet Commanders would then have to be ready to act before landfall. The opportunity to do this existed in the case of Charley.

b. Hurricane Frances. Hurricane Frances made landfall in the middle portion of the eastern Florida coastline as a Category 2 storm (Fig. 7) about three weeks after Charley. After crossing over the Florida peninsula, Frances briefly passed over the extreme northeastern waters of the Gulf of Mexico, and made a second landfall as a tropical storm on the Florida panhandle. When Frances was approaching Florida, just over 72 h from landfall, most meteorological forecast models were in fairly close agreement in describing Frances' translation north of Grand Bahamas (Fig. 7)[4]. The consensus of these tracks, which up to that point had been performing well (Fig. 7), indicated that Frances was heading for a landfall along the northern Florida coast, which caught the attention of Fleet Commanders. However, individual models then diverged somewhat after 36 h to 48 h in these model forecasts. Some models indicated a continued west-northwest track across the Central Florida peninsula, while other models forecast a sharper poleward turn toward the Georgia-South Carolina border. With these alternate track scenarios that bracketed the Mayport Naval Station and NAS Jacksonville, forecasters and Fleet Commanders likely wondered which scenario was correct. The official guidance predicted a track somewhat to the left (west) of consensus (not shown), which turned out to be a reasonably good 72-h forecast. However, without metrics for the uncertainty in the individual forecasts (or the consensus, for that matter), the chance of wasteful, unnecessary preparations and a sortie remained so long as any forecast guidance predicted a track close enough to Mayport to threaten the Naval Station with > 50 kt winds (Fig. 7).

At 2300 EDT 1 September, the NHC discussion began to address this dilemma: "…00Z upper-air data indicate that the 18Z NOGAPS and 12Z UKMET models have verified the 00Z 500 mb ridge and heights the best…while the 18Z GFS and GFDL models were much too weak…," which implied that the former models (which had the more west-northwesterly track forecast) would provide a better track forecast than the latter (which forecast a more poleward turn) due to better verification of the subtropical ridge and thus the steering flow for Frances. In spite of this discussion the NHC did not adjust the official track forecast, and waited until the 0000 UTC analyses (with GPS dropsonde data included) were available. In the 0500 EDT NHC discussion that followed the 0000 UTC 2 September model runs depicted in Fig. 7, the NHC adjusted the official track forecast by nudging it west toward the NOGAPS and UKMET solutions. (There is no UKMET track in Fig 7). Since NOGAPS handled this particular landfall

[3] The Inland Wind Model, which is a diagnostic empirical tool developed and used by the NHC, provides some guidance for wind intensity inland based on landfall Saffir-Simpson scale intensity and translation speed. It will be discussed again later in the Summary and Conclusions section.

[4] Of course, there are many more individual models and ensembles available to the NHC forecaster than the few shown in the ATCF graphics included here. In the interest of clarity, brevity, and making relatively basic points, only a handful of model TC track forecasts are displayed herein.

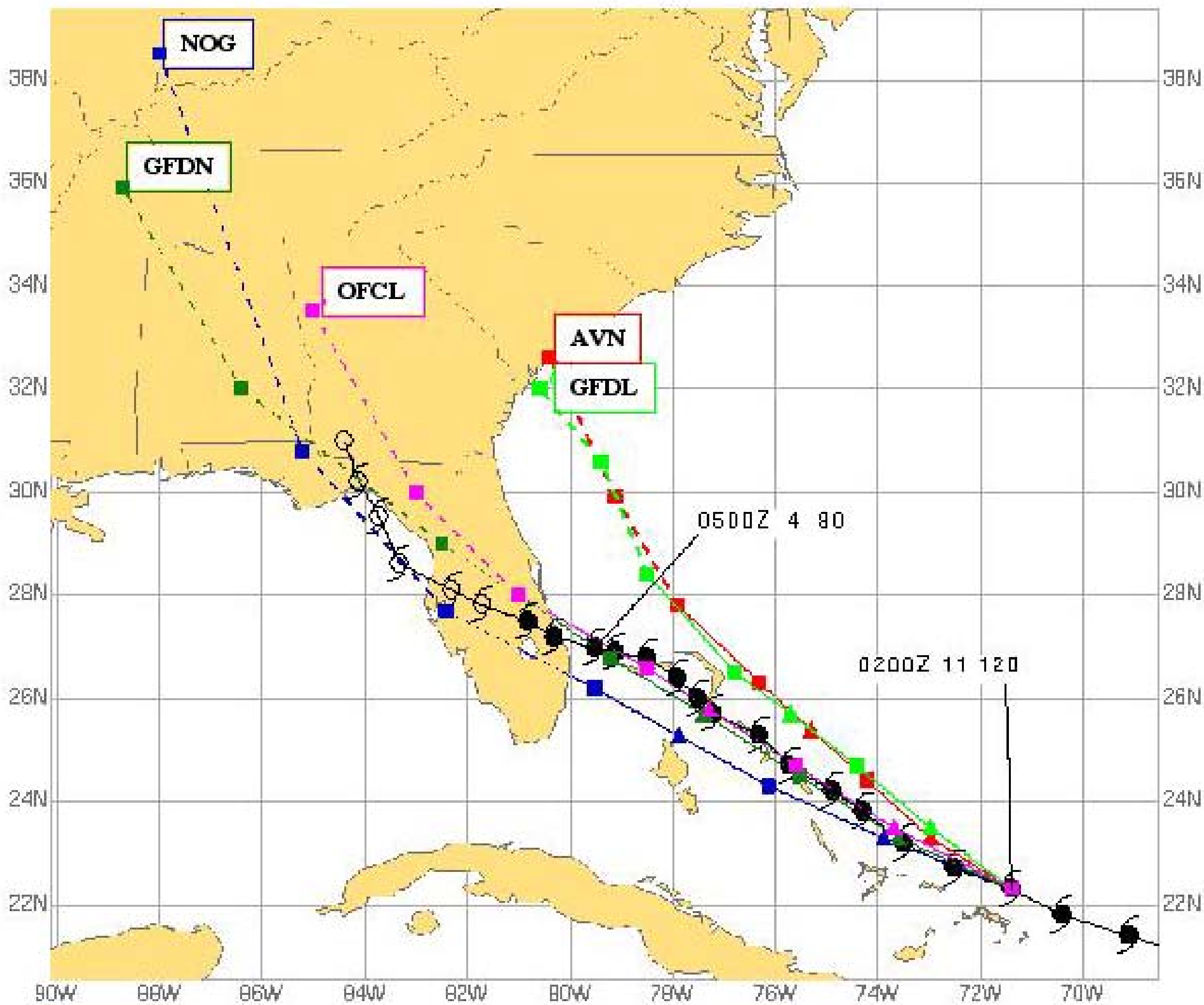

Fig. 7. 120-h forecasts from 0000 UTC 2 September 2004 of the track of Hurricane Frances. Hurricane (Tropical Storm) Frances positions depicted by black hurricane (tropical storm) symbols every 6 h, and labeled in black (DDHH, in UTC) at the initial location and the 72-h position. Forecasts made by NOGAPS (NOG, blue), the NCEP AVN (AVN, red), the GFDL (GFDL, light green), GFDN (GFDN, dark green) and the NHC Official forecast (OFCL, purple) depicted at 12-h (triangle), 24-h (square), 36-h (triangle) and 48-, 72-, and 96-h (squares). Courtesy of NRL Marine Meteorology Division via the Automated Tropical Cyclone Track Forecasting System (ATCF).

forecast well[5], it is not surprising then that the overall consensus (which included NOGAPS), and the official forecast that is nudged toward the NOGAPS solution, performed well with respect to landfall. The 0000 UTC 4 September 2004 official forecast (Fig. 8) depicted much stronger convergence of the individual model track forecasts, and provided Fleet Commanders with a high confidence forecast of landfall in Central Florida, well to the south of Naval Station Mayport and NAS Jacksonville. Later, WSR-88D Doppler Radar and geostationary satellite observations on 4 September confirmed the turn of Frances' to the west (notice the turn west in

[5] That is, with low cross-track error, even though along track error is significant at the end of the forecast cycle, so that error in the timing of landfall and acceleration inland is pronounced.

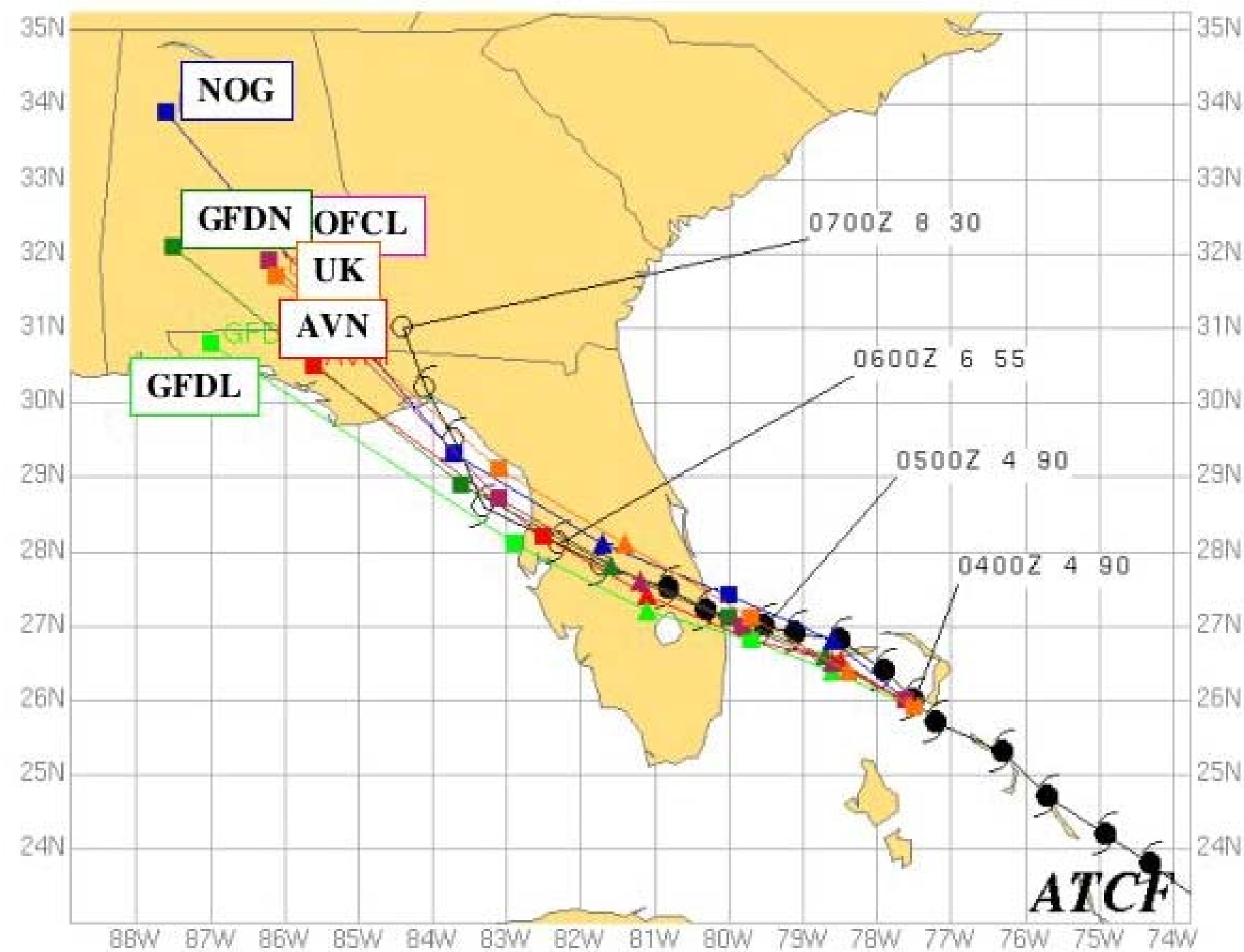

Fig. 8. As in Fig. 7, but from initial time 0000 UTC 4 September 2004, and including the UK Met Office forecast (UK, orange). Courtesy of NRL Marine Meteorology Division via the Automated Tropical Cyclone Track Forecasting System (ATCF).

the official track around 1200 UTC 4 September depicted in black in both Figs. 7 and 8), and verified the prediction that no sortie would be necessary. The main point to be made here is that a spread among model tracks poses a dilemma for forecasters providing guidance to Fleet Commanders, because the question becomes which solution is correct, and so long as any track forecast threatens a Naval Station, what is the likelihood that such a solution is accurate and will require a sortie or preparations according to CORs? Concern about whether or not Frances would continue to head toward Naval Station Mayport, and about the structure of the storm (i.e., the radius of sustained >50 kt winds at landfall), made it a worrisome hurricane until later on 4 September, well after verification that the westward track forecasts were correct.

c. Hurricane Ivan. At 2300 EDT, 09 September 2004, the NHC mentioned high confidence based on close agreement in the model guidance in the first 36- to 48-h interval of its track forecast, which took the storm over Jamaica and into western Cuba (Fig. 9). In the 1100 EDT 10 September discussion NHC explained, "…there is still high confidence in this early portion of the forecast but…it becomes uncertain after the hurricane crosses over Cuba when guidance shows that the hurricane could continue over the Gulf of Mexico or could turn north-northeast

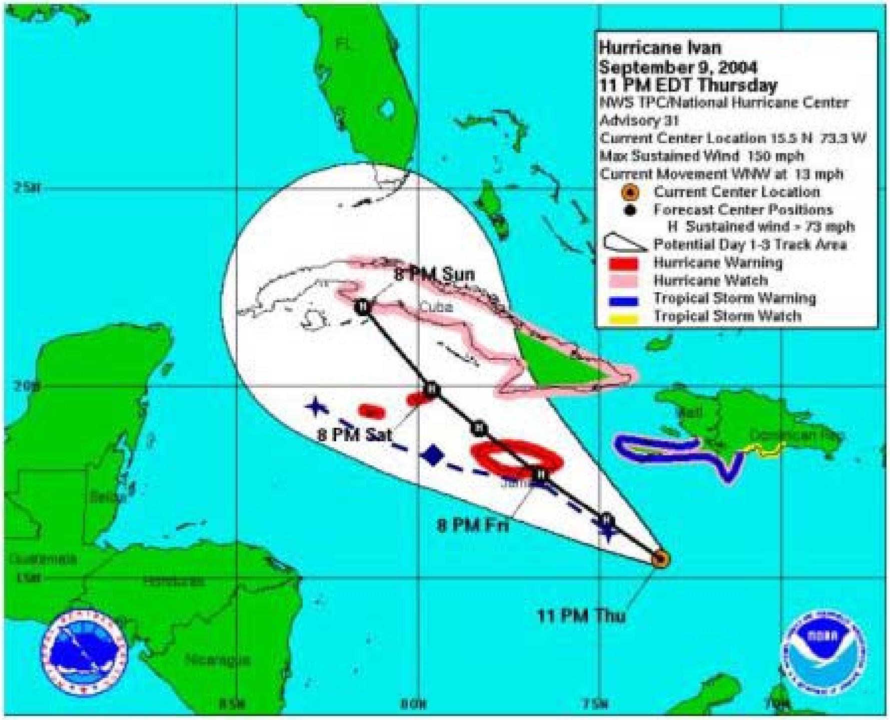

Fig. 9. NHC 72-h forecast track for Ivan (solid black line, forecast times as marked), with positions marked at 12, 24, 36, 48 and 72 h, compared to actual track (dashed, blue) from 1200 UTC 10 September through 0000 UTC 13 September (beginning and end times represented with blue stars). The blue diamond is the actual position of Ivan relative to the 48-h forecast position (NHC, 2004).

over Florida. In fact, this has been the case for the past couple of days. The official forecast does not favor one scenario more than the other." Six hours later, in the 1700 EDT 10 September 2004 discussion, NHC stated "models are becoming in better agreement on a track across the Eastern Gulf of Mexico. Although the official forecast could have been shifted a little westward due to the new guidance…it is not prudent to make a change at this time." A desire to maintain continuity overruled the urge to favor the western solutions by nudging the official forecast even farther to the west. Thus, in the course of 10 September, the 96-h guidance available to Fleet Commanders evolved into one which forecast that Ivan would enter the Gulf of Mexico and threaten Naval Station Pascagoula and Fleet interests in Mobile Bay, yet still pose a threat to the western coast of Florida. This situation closely resembled the first scenario presented in the previous section (Fig. 1). Later, Ivan wobbled to the west 10-11 September, so that 48 h into that forecast Ivan was nearly 100 n mi south of where it was predicted to be (notice the cross-track error suggested by the blue diamond on the dashed track).

It is important to note that on 8 September 2004 a significant change in the cumulus convective parameterization was implemented in the NOGAPS model. The details of that change will not be discussed here. Despite occurring during hurricane season, this change may not have been well publicized, and specifically no guidance was released as to improvements in the track and intensity forecasts based on the test cases. As a result, the NHC forecasters were unaware of the change and the potential impact on NOGAPS TC track and intensity forecasts, which indeed had much higher accuracy in the Atlantic Basin after 8 September.

Once Hurricane Ivan passed south of Hispaniola and approached Jamaica, model track forecasts suggested it would (i) make landfall on the west coast of Florida and pass over the peninsula with sufficient intensity to endanger Naval Stations near Jacksonville; or (ii) move northwestward into the Gulf of Mexico and threaten the Naval Station at Pensacola, or Gulf Coast shipyards, and Navy assets along the Mississippi and Alabama coastlines. Which solution was correct? Model track guidance and the official forecast for 0000 UTC 11 September 2004 are depicted in Fig. 10. Notice the relatively good agreement Ivan would move across extreme western Jamaica, and then over western Cuba. Then, the forecast path was extended into the eastern Gulf of Mexico, with NOGAPS (blue) and the NCEP AVN (red) as the outliers. Notice as well the official forecast and consensus track (Fig. 11), were both split down the middle of this divergent solution set (as presented in the case of Frances above). In this solution set, Fleet Commanders were faced with a hurricane that could potentially threaten the Florida west coast in just over 72 h (and Naval Stations in the vicinity of Jacksonville in 96 h) or instead make landfall closer to Pensacola and Mobile Bay, which raised concern for units at sea in the Gulf of Mexico, or those berthed in the Naval Stations or shipyards in Pascagoula. Mobile, and Ingleside, TX. The point here is that ***decisions facing the Fleet Commander were not made any easier by official guidance placed in the middle of divergent solutions, without some uncertainty metrics associated with that consensus forecast track***. The 0500 EDT 11 September NHC discussion diagnosed Ivan's wobble to the west (Fig. 10) and noted that track guidance for four models (marked AVN, GFDL, NOGAPS, and UK in Fig. 10) had shifted west (perhaps due to Ivan's westward change in track). However, the official forecast was kept close to the consensus track in Fig. 11.

A significant development relative to Ivan's track is included in the NHC discussions at 1100 and 1700 EDT 11 September. Water vapor imagery was used to diagnose a mid-level ridge over the eastern Gulf of Mexico and Florida (not shown), which would tend to steer Ivan away from Florida into a more west to west-northwest track. Accordingly the 0000 UTC 12 September model run shifted further westward so that all models predicted that Ivan would enter the eastern Gulf of Mexico and threaten the Florida panhandle (Fig. 12). Finally, the official forecast was turned to the west rather than simply follow consensus, but now it was actually east of consensus (compare Figs. 11 and 13), even though the last 48 h saw most model guidance (and thus its consensus) systematically shift westward. In the 2300 EDT 11 September discussion, NHC predicted that the ridge north of Ivan (discussed by NHC at 1100 and 1700) would weaken while a "weak low moves southeastward from the lower Mississippi Valley region." This would have supported the official forecasts, if it verified, but it did not. It seems that the official forecast continued to be weighted in favor of the eastern outliers (the UK and AVN tracks in Fig. 12), given that previous track forecasts to the west continued to verify best. In fact, adopting consensus (compare Figs. 11 and 13) as the official forecast would have been a more accurate forecast, although clearly the western outliers outperformed the eastern outliers and the official forecast. The official forecast 72 h before landfall finally respected the performance of the western outliers (as most of the model guidance had begun to converge westward), and it was an accurate prediction of landfall on the westernmost part of the Florida panhandle (not shown). With confidence in that forecast, Fleet Commanders felt that the threat to Jacksonville was minimized, and they expected landfall near Mobile, Pensacola, or possibly even Pascagoula 72 h later.

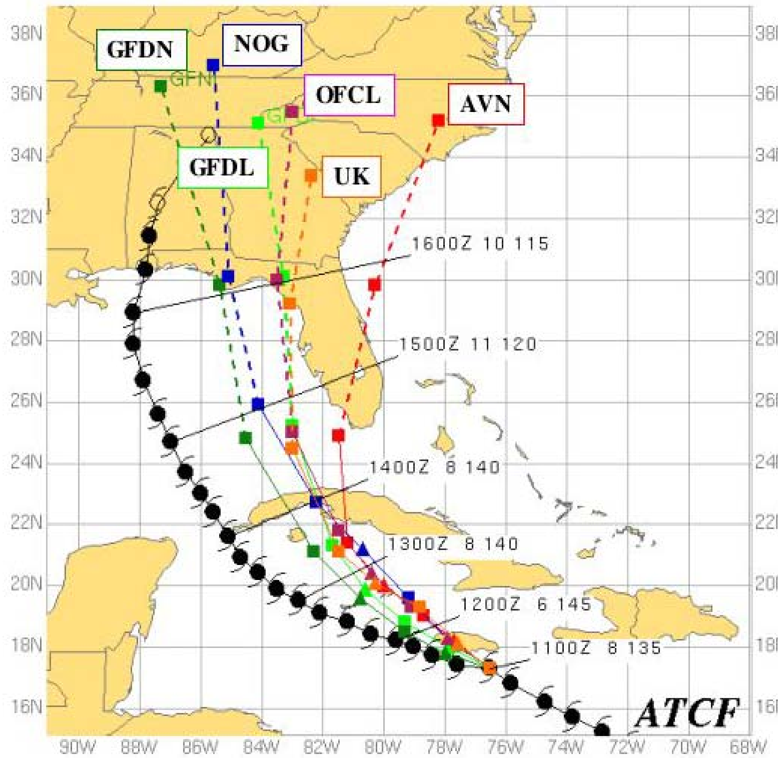

Fig. 10. As in Fig. 8, except for the case of Hurricane Ivan from 0000 UTC 11 September 2004. Courtesy of NRL Marine Meteorology Division via the Automated Tropical Cyclone Track Forecasting System (ATCF).

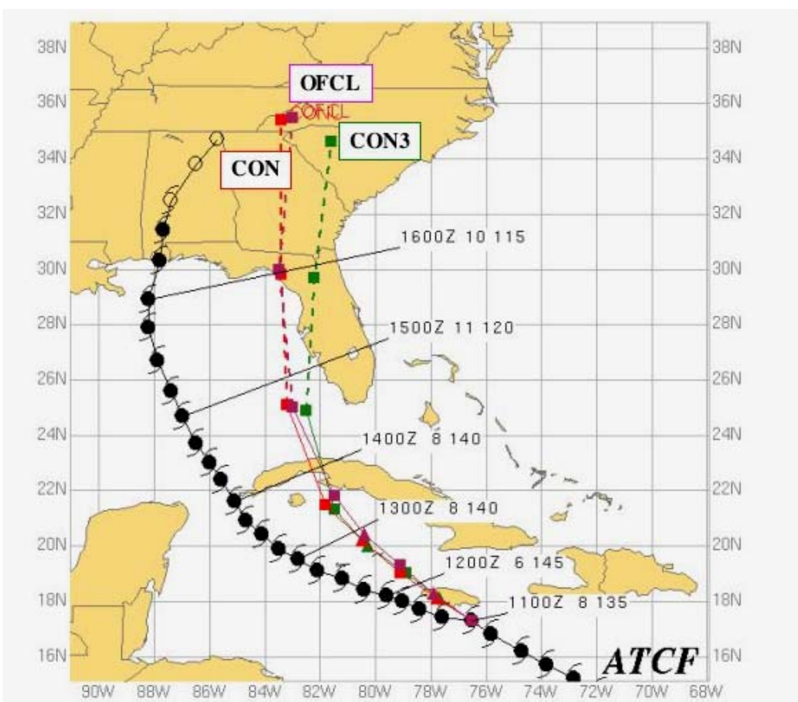

Fig. 11. As in Fig. 10, but with the NHC Official forecast (OFCL, blue), the consensus forecast based on the models depicted in Fig. 7 (CON, red) and the consensus forecast without NOGAPS or the GFDN (CON3, green). Courtesy of NRL Marine Meteorology Division via the Automated Tropical Cyclone Track Forecasting System (ATCF).

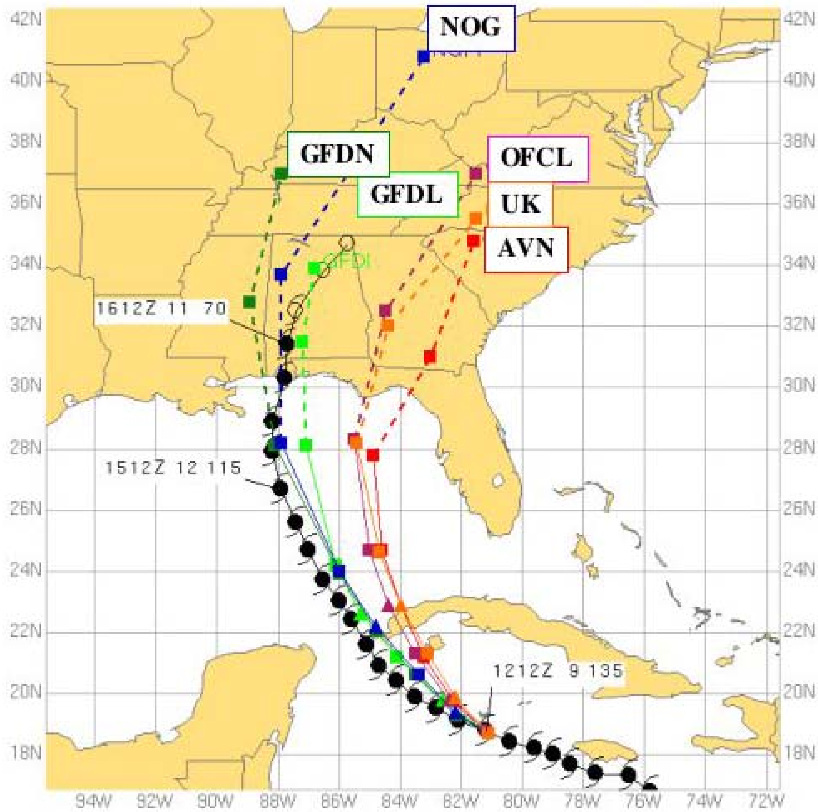

Fig. 12. As in Fig. 8, except for the case of Hurricane Ivan from 0000 UTC 12 September 2004. Courtesy of NRL Marine Meteorology Division via the Automated Tropical Cyclone Track Forecasting System (ATCF).

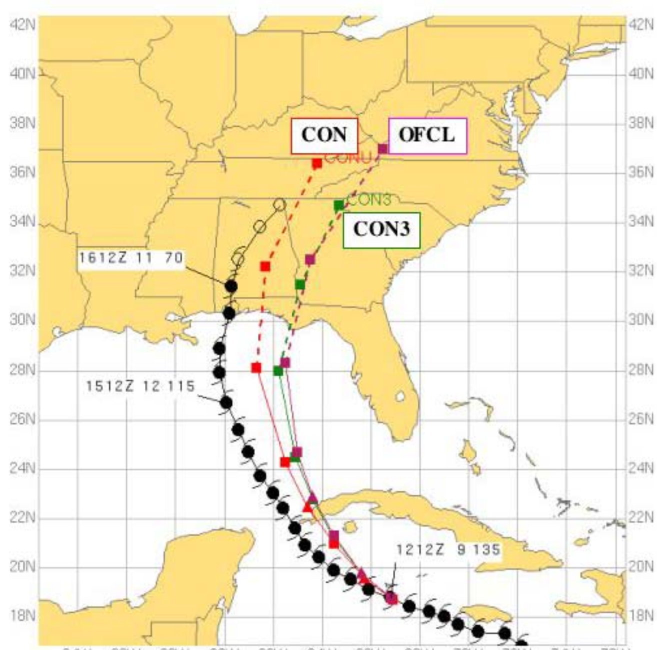

Fig. 13. As in Fig. 8, except for the case of Hurricane Ivan from 0000 UTC 12 September 2004. Note that the official forecast is to the right of consensus. Courtesy of NRL Marine Meteorology Division via the Automated Tropical Cyclone Track Forecasting System (ATCF).

The main point to be made in the case of Ivan is that after the model track forecasts presented two distinct scenarios on 10 September, changes in the synoptic environment were diagnosed and described well in the NHC discussions presented above. The official forecast first mimicked consensus, (which is not unreasonable considering the track forecast spread, and that consensus tracks perform best statistically (Goerss et al 2004)), but made no adjustment in spite of observational evidence and numerical guidance of a number of models (Figs 10-13). Since such evidence existed in the case of Ivan, what was the compelling physical reason that NHC erroneously placed the official forecast consistently to the right of consensus (which was outperforming the official forecast because western outliers were verifying well)? Does the requirement of issuing consistent forecasts obstruct the use of good scientific judgment? What made the scenario of widely divergent guidance difficult for Fleet Commanders was the lack of some measure of the uncertainty associated with the individual model forecasts, or their consensus, which would have allowed them to properly focus their preparedness actions in the region of highest risk while avoiding unnecessary disaster preparedness actions in regions of acceptable low risk.

d. Hurricane Jeanne. One week after Ivan's landfall, and about five weeks after Charley's landfall, Jeanne began to translate westward to become the fourth hurricane to threaten Florida in 2004. By the 2300 EDT 21 September NHC forecast discussion, all of the model guidance predicted that Jeanne would loop anticyclonically before translating west and then poleward. In the 1100 EDT 22 September discussion, the NHC described a "deep-layer high centered over Ohio with a ridge extending southeastward to near Bermuda " which was moving slowly eastward. The expectation was that the clockwise flow associated with this ridge would accelerate as the ridge moved east, thereby steering Jeanne northward. The NOGAPS track (again) was a western outlier; that is, it predicted slower translation eastward of the ridge, so that Jeanne would move farther west and across central Florida before turning poleward.

In the very next discussion at 1700 EDT, the NHC announced that the model guidance had "made a major westward shift" as the ridge steering Jeanne was forecast to move more slowly to the east. At 2300 EDT, the NHC mentioned in its discussion that most models, including the consensus and the FSU Superensemble (not shown), predicted Jeanne would turn poleward only after moving very near or over the Florida east coast, and that even the AVN guidance that had previously turned Jeanne poleward east of Florida now forecast Jeanne would translate over Florida. In hindsight, this progression suggested that the main synoptic influence (the deep-layer ridge over Ohio) on Jeanne's translation was moving eastward slower than anticipated so that the models were now moving Jeanne farther west before turning it poleward. This increased the risk of landfall on the east-central coast of Florida, and implied that the NOGAPS forecast that was rejected 12 h earlier may have actually been sound guidance. On September 22, the official track forecast shifted west, although the 2300 EDT 22 September discussion noted the temptation to shift it even farther westward was not done because it was "important to keep continuity" with the previous forecasts.

By 1100 EDT 23 September, more than 72 h before Jeanne's landfall, the NHC predicted a central Florida landfall with an along-coastline (cross-track) error of only 60 n mi (Fig. 14, based on 0600 UTC model forecast tracks). Notice that the official track forecast was for recurvature along the Florida east coast, and that once again, it closely followed consensus between a few

western and eastern outliers (Fig. 15). Despite an excellent path prediction, the western outliers (NOGAPS and GFDN) models accelerated Jeanne too much (significant along-track error) at the end of the forecasted period (Fig. 14). Based on the official track forecast, Fleet Commanders still had to be concerned about the threat to Naval Station Mayport and NAS Jacksonville, even though some models suggested that Jeanne would move farther west before recurving, and that guidance as a whole had shifted west over the previous 24 h.

Up to this point, the NHC discussions were extremely useful in crystallizing the threat to the Florida East Coast with 72 h to spare. In the forecasts that followed, Fleet Commanders would have inquired whether or not the forecast tracks were continuing to shift westward, which would have reduced the threat to the Naval installations near Jacksonville, and precluded the need for a sortie. In the NHC discussion at 2300 EDT 24 September, it was mentioned that only a few more hours of westward motion beyond that previously forecast would result in large cross-track errors in predictions of Jeanne's recurvature. Notice that in the 25 September 0000 UTC forecasts (Fig. 16), the landfall points in the individual models displayed were only separated by 80 n mi, and the individual 48-h forecasts were separated by approximately 100 n mi from west to east, cross-track. Though this distance is small, it is also close to 75% of the maximum width of the Florida Peninsula. Recall that the principle trigger for a sortie is expectation of > 50 kt winds on station. Every model track forecast except the western outliers in Fig. 16, as well as consensus and the official forecast (Fig 17) would likely have satisfied that criteria, so any amount of continued westward motion before recurvature as discussed by NHC at 2300 EDT 24 September was of tremendous importance to the Fleet Commander! Notice that the official track forecast placed landfall far to the south of Mayport, (Fig. 16) and once again was east of consensus (Fig. 17) in its forecast of recurvature. In this case however, exact landfall predictions were less important to the Fleet Commander than determining whether or not the western outliers would verify, and thus keep Naval Station Mayport out of the region of > 50 kt winds once Jeanne made landfall and recurved. Indeed, individual model guidance, consensus, and the 0500 EDT 25 September NHC official forecast, which preceded landfall by less than 24 h, continued to suggest a potential threat to the Naval Station Mayport and Naval Air Station (not shown).

A further complication was that Jeanne intensified from 23 September (85 kt) to landfall (the NHC discussion of 0500 EDT 26 September reported the Melbourne WSR-88D Doppler winds were between 100 to 115 kt during the night of 25-26 September, making Jeanne a Category Three storm). In its 2300 EDT 25 September discussion, the NHC warned that hurricane force winds could be anticipated up to 100 n mi from the track of the storm. Had Jeanne intensified further and made landfall 100 n mi farther north, or had weakened more slowly so that it had not been downgraded to a tropical storm before crossing into the Gulf of Mexico, it is likely that the Naval Stations in the Jacksonville area could have experienced sustained hurricane-force winds for some period of time. Even though the official forecast called for the storm to recurve just inside of Florida's east coast, the combination of sufficient confidence in a landfall near 27.5 N (notice the official forecast and consensus landfall location in Fig. 17), the good performance of westernmost outliers, and the tendency of the remaining models to be consistently too far east in their track predictions likely played a role in the decision not to sortie from Mayport, as > 50 kt winds were not expected on station.

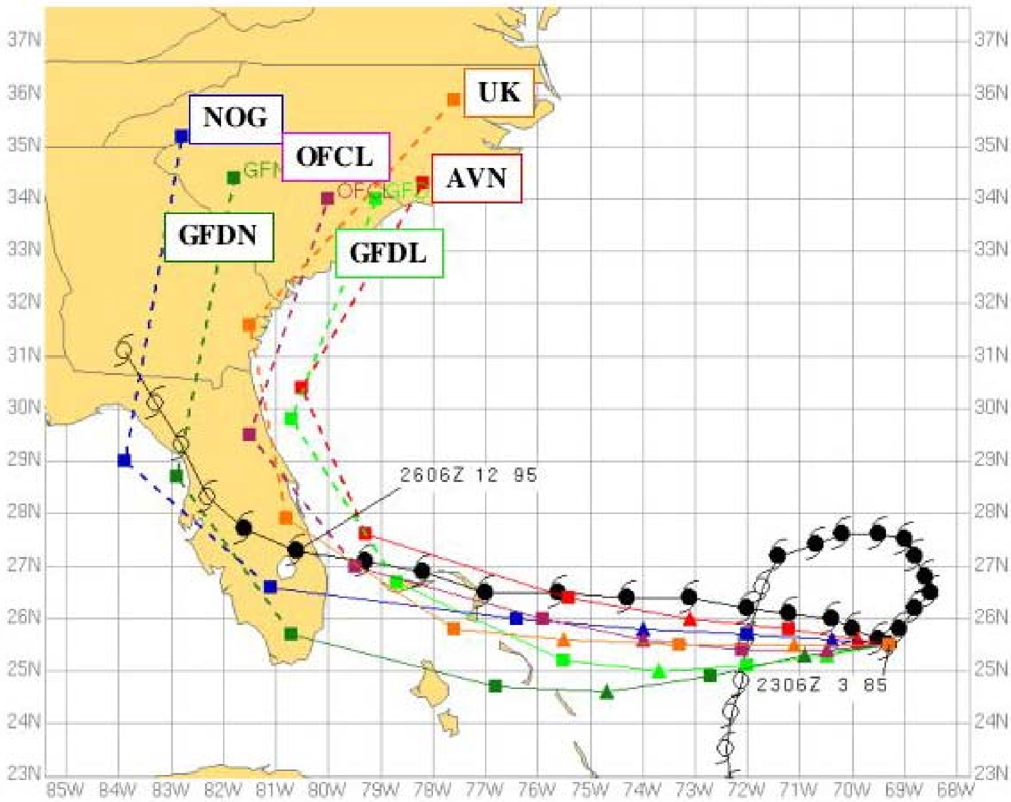

Fig. 14. As in Fig. 9, except for a 96-h forecast from 0600 UTC 23 September 2004 in the case of Hurricane Jeanne. Courtesy of NRL Marine Meteorology Division via the ATCF.

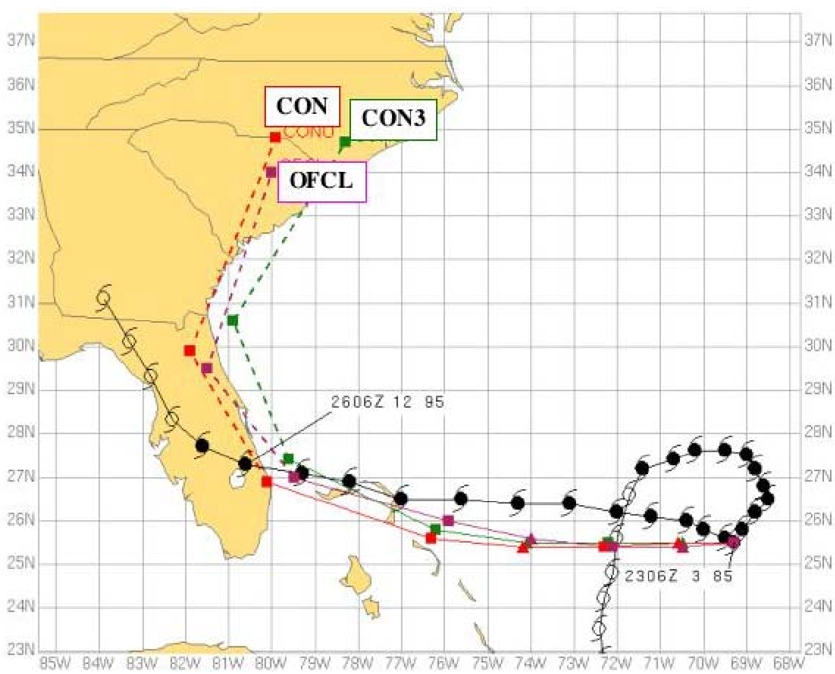

Fig. 15. As in Fig. 8, except from 0600 UTC 23 September 2004 for the case of Hurricane Jeanne. Courtesy of NRL Marine Meteorology Division via the ATCF.

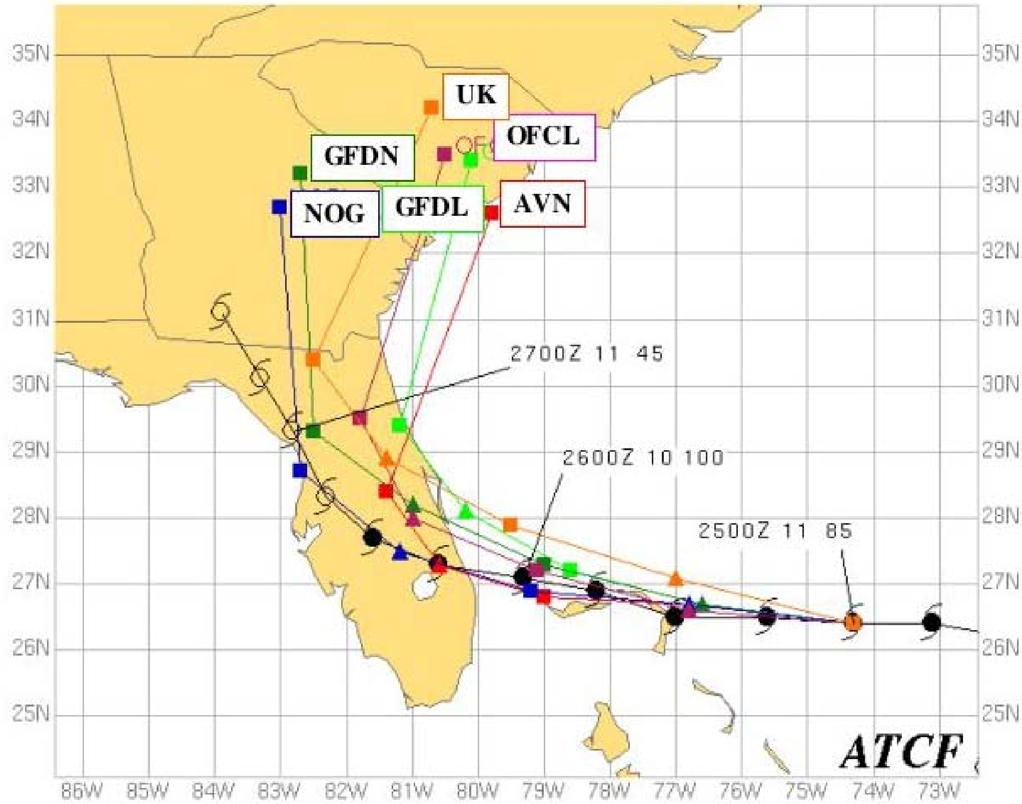

Fig. 16. As in Fig. 9, except for a 72-h forecast from 0000 UTC 25 September 2004 in the case of Hurricane Jeanne. Courtesy of NRL Marine Meteorology Division via the ATCF.

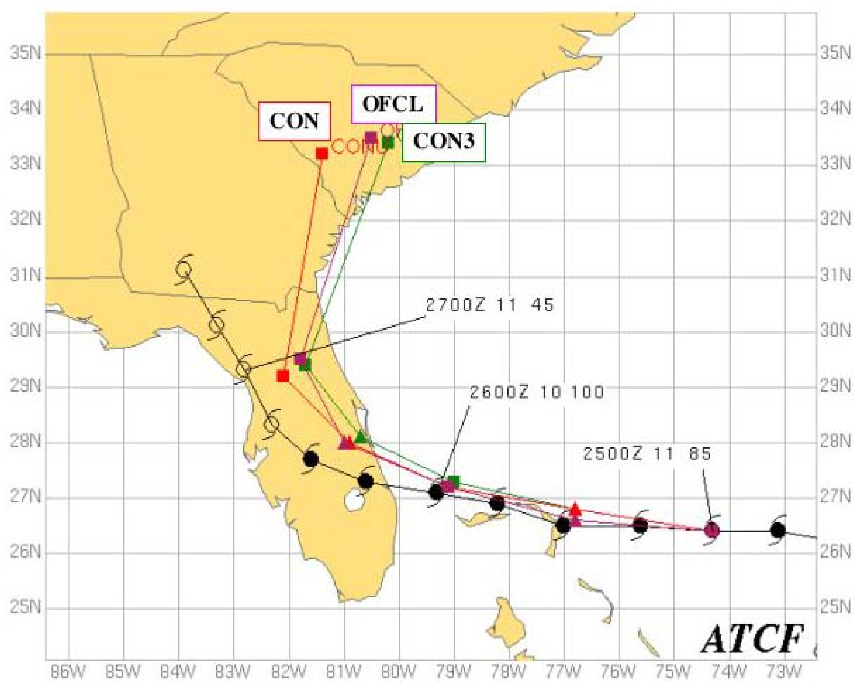

Fig. 17. As in Fig. 8, except from 0000 UTC 25 September 2004 for the case of Hurricane Jeanne. Courtesy of NRL Marine Meteorology Division via the ATCF.

4. Summary and Conclusions.

The previous two sections described the U. S. Navy's criteria for TC preparedness and disaster mitigation, especially with respect to Naval Stations and sorties of ships and aircraft, and the impact of specific track and intensity forecasts on decisions faced by Fleet Commanders in the cases of Hurricanes Charley, Frances, Ivan and Jeanne of 2005. In the case of Charley, the USS Yorktown (CG 48) left Pascagoula, MS early, and a sortie was ordered from Mayport. Winds at Mayport were observed to be 32 kt (gusting to 47 kt) as the storm passed 34 n mi to the south. The rapid spindown of Charley as it crossed Florida north to south meant that even though the decision to sortie was correct at the time, the storm passage was benign enough that ships could have remained in port. However, a decision to stay could not have been made because of the uncertainty in predicting Charley's spindown, especially given Charley's rapid intensification just before landfall. The added cost to the Navy for that sortie was set by CFFC at $500,000[6]. In the case of Hurricane Frances, although no sortie was ordered, the decision to remain in Mayport was likely the "closest call" in terms of the risks. Hurricanes Ivan had a direct impact on the U. S. Navy because of the damage inflicted on Naval Station Pensacola. Hurricane Jeanne had a minor impact once the decision was made not to sortie with some confidence that the likely track would be south and west of Mayport and Jacksonville. Considering the uncertainty regarding Jeanne's exact recurvature path, and long weeks of hurricane fatigue since Hurricane Charley that preceded her landfall, Fleet Commanders could not let their guard down with Jeanne until the last possible moment. In the cases of Frances and Jeanne, maximum winds observed were 50 kt (gusting to 75 kt), and 45 kt (gusting to 55 kt), respectively. With no damage reported in either case, the decision not to sortie in each case was correct and based on the cost of the Charley sortie, saved $1,000,000. [7]

Based on review of NHC forecast discussions of TC track and intensity, as well as selected model track forecast performance comparisons and other data, some important points regarding problems faced by Fleet Commanders in these four "Florida Hurricanes" can be gleaned from the previous section:

a. 50 kt wind and 12 ft seas criteria. These represent the two physical parameters that determine execution and timing of a sortie. Sustained winds anticipated on station remain the primary concern in determining whether or not a sortie is necessary. If >50 kt sustained winds are expected, a sortie will be ordered and must be completed before the arrival of >12 ft seas. Some sorties take longer than others too; recall the case of Charley, where the sortie in Mayport was commenced just as Charley began to make landfall. If Naval Station Mayport was homeport to the same number of ships as in Norfolk, that sortie decision would have had to been made several hours earlier to allow completion of a larger sortie. Ultimately, successful operational risk management in sortie decisions requires clear graphical demarcation of the radii or boundary of >50 kt winds and >12 ft seas in both analyses and forecasts. These metrics are of greater value to the Fleet Commander than pinpointing the exact location of landfall. Unfortunately, the 50 kt wind criteria is a TC intensity metric, and at present, dynamic model forecasts of TC

[6] This was a "Mayport" sortie; a "Norfolk" sortie would have involved many more ships and thus would have been far more expensive. It would also have taken much longer to complete.

[7] Wind reports and costs associated with Charley, Frances, and Jeanne reported by CFFC's senior METOC Officer in telephone conversation as well as in a Powerpoint brief delivered by e-mail.

intensity and structure (i.e., wind intensity profiles within the inner- and outer circulations of the TC) are not skillful, so improvements here are urgently needed.

b. Track and Intensity Forecasts. Accurate track and intensity forecasts remain crucial for storm avoidance at sea. A numerical model that failed to produce an accurate track and intensity forecast will likely perform badly in its prediction and depiction of regions of > 50 kt winds and > 12 ft seas. In the past, Fleet Requirements in track forecast accuracy were expressed in terms of track error (in n mi) at 24 h increments in the forecast cycle. Because SC C is set 48 h before an anticipated sortie, and considering the importance of the region of > 50 kt winds and > 12 ft seas, ***future requirements should include a measure of uncertainty in the timing of the onset of 50 kt winds and 12 ft seas on station, starting at least 72 h prior to forecast landfall***.

c. Wind dissipation after landfall. At present, the Inland Wind Model used at NHC (Kaplan and DeMaria, 1995) employs empirical methods for determining wind decay based on Saffir-Simpson Scale intensity observed at landfall as well as the translation speed of the TC to determine inland winds in increments of 15 kt (at http://www.nhc.noaa.gov/aboutmeow.shtml). Improvements, to include a skillful, prognostic capability and more sophisticated physics with high resolution, realistic representations of ground type, soil moisture, terrain, and the forecasted TC translation path inland, would well serve the needs of Fleet commanders, should > 50 kt sustained winds be anticipated even if the TC approaches from the landward side.

d. Individual Model Performance Traits and Quantifying Prediction Uncertainty. The sensitivity of the NOGAPS tracks to the change in the convective parameterization scheme illustrates an important point. Such significant changes in a guidance model should be well publicized, along with the test results that describe the impact on TC track and intensity forecasts.

In the case of widely divergent model guidance, uncertainty measures associated with the official forecast would help the Fleet Commander determine the proper course of action, since minimizing operational risk over large areas is impossible without skillful estimation of the likelihood of a TC posing a danger to a Naval Station or ship(s) at sea. These uncertainty measures would be most useful if they were crafted in terms of the risk management concerns of the Fleet Commander (regions sustained winds exceeding 50 kt, and seas exceeding 12 ft, determined at least 72 h before landfall), but should at a minimum serve as a measure of confidence in the forecast guidance. How this uncertainty increases or decreases with time is also a useful metric for assessing skill and confidence associated with track forecasts. Considering that at present most warning centers are reluctant to stray too far from consensus without strong meteorological evidence compelling them to do so,[8] uncertainty metrics describing the consensus track derived from a large ensemble of skillful dynamic model track forecasts would be most useful. The Naval Research Laboratory Marine Meteorology Division is developing a Predicted Consensus Error (PCE) product for the western North Pacific. Currently, the PCE product includes a 70-75% confidence circle around the consensus forecast position, which describes a region within which one can have 70-75% confidence that the TC will be located within that circle at the forecast time indicated. Such a product would be an

[8] Personal Communication, with Dr. Jim Goerss and Buck Sampson, NRL Marine Meteorology Division, April 2005

excellent start toward addressing the Fleet Commanders urgent need for consensus and model guidance forecast track uncertainty metrics.

e. Sea Surge Forecasts. Specific surge forecasts are also essential, since small craft that cannot be trailered or drydocked in a safe shelter are usually sent to safe havens in inland waters. If a sortie is not ordered, the elevation of the expected storm surge is critical to planning the foul-weather mooring of larger vessels pierside or at anchorage. Preller et al. (2004) described the "PC Tides" ocean model storm surge associated with Hurricane Isabel, and showed the forecasts of storm surge verified well with observations at selected Atlantic Coast and Chesapeake Bay locations. Despite being a relatively weak hurricane (particularly once Isabel translated west of the Chesapeake Bay), the associated storm surge was nonetheless extreme. Close coupling of an ocean model with high-resolution bathymetry, tidal cycles, and atmospheric wind forcing should provide excellent forecasts of storm surge that are specific to the desired location of interest.

In many ways, the impact of the four Florida hurricanes upon the fleet could have been much worse. It is acknowledged that the teamwork between the NHC, FNMOC, NRL, and Navy forecasters, produced the best-available guidance at the time to Fleet Commanders. With the appropriate track forecast uncertainty metrics, as well as improved techniques for predicting TC intensity and structure, surge, swell, and diminishing hurricane winds, forecasters could tailor the support provided to the Navy meteorologists who brief Fleet Commanders so that it address specific Fleet requirements, while at the same time safeguarding the public with the kinds of forecasts and advisories they need.

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